CO_2-GAIM. Fluid-assisted injection technology is an established method for producing complex hollow parts that cannot be implemented with conventional cores. The choice of fluid has a significant impact on part quality and cycle time, and the quality of the inner surface. What is not so well known is that carbon dioxide, acting as injection medium, offers huge potential to reduce part costs and energy input and to improve part quality – without additional effort.

Various handles made by the gas-assisted injection technique (photo: TiK)

Untapped Potential in Gas-Assisted Injection Molding

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Fluid-assisted injection technology (FIT) is an umbrella term for injection molding methods in which an injection fluid displaces a liquid polymer from the core of a molded part. Hobson [1] in a patent dating back to 1939 described the ways in which this can happen. This basic idea spawned several methods in the 1980s that can be classified by the manner in which the melt is displaced. The most important are:

- the short shot process,
- the full shot or spill-over process,
- the pushback process, and
- the floating core process.

The various types of melt displacement aside, experiments were also conducted on different injection fluids in the late 1990s that led to water-assisted (WAIM) and the gas-water-assisted injection technique (TiK-WIT process) [2, 3]. Water itself makes an extremely attractive injection fluid for high-volume production of parts, primarily because of its great cooling action and its low cost. However, water has drawbacks for the process, because the parts need to be drained or dried and because leaks can give rise to serious damage and costs.

This article will now present another fluid, which is also well known but has not yet established itself for fluid-assisted injection, namely carbon dioxide (CO_2). It is the physical properties of CO_2, which are rather atypical of gases and will be discussed later, that make this gas so interesting for the gas-assisted injection technique (GAIM).

Benefits of CO_2 Gas-assisted Injection

A comparison of which fluid is suitable for which parts reveals that water and CO_2 are equally favorable in terms of energy input for fluid-assisted injection and attainable cooling or cycle times **(Table 1)**. In addition, the GAIM process proceeds more or less as readily with CO_2 as it does with nitrogen (N_2).

A look at the physical properties of CO_2 clearly shows its benefits [4]. Its density starts to increase markedly only from 150 bar on, approaching that of water as the pressure continues to rise **(Fig. 1)**. Another interesting aspect is that CO_2 can be liquefied at room temperature simply

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by raising the pressure to 60 bar. Nitrogen, however, cannot be liquefied at room temperature, and is a liquid only at cryogenic temperatures (-196 °C at atmospheric pressure).

CO_2 is usually delivered as a liquid in cylinders, cylinder bundles or tanks. In this physical state, the heat capacity, c_p, of CO_2 (3.0 $\mathrm{kJ\,kg^{-1}\,K^{-1}}$) is three quarters that of water (4.178 $\mathrm{kJ\,kg^{-1}\,K^{-1}}$) and almost three times that of nitrogen (1.04 $\mathrm{kJ\,kg^{-1}\,K^{-1}}$). Another physical advantage of CO_2 is the high heat of expansion which the gas extracts from its environment as the pressure falls. The totality of these physical properties explains the huge cooling potential of CO_2, which can shorten the cooling time by half, compared with nitrogen.

A practical advantage of CO_2-GAIM is that the gas has a very good cleaning effect. Annular gap injectors virtually stop clogging up and can be thoroughly cleaned by simply purging with CO_2 between two production cycles. The process is more stable as a result because there is no danger that the injector will gradually clog up.

Any assessment of the energy needed to compress the fluid must distinguish between whether compression takes place in the liquid or the gaseous state. If the CO_2 is in liquid form, the corresponding pumps have a very high flow rate and the amount of energy needed for pressurizing is more than two orders of magnitude lower than that for compressing gaseous nitrogen. True, nitrogen can also be pressurized in the liquid state, but only from a cryogenic liquid-gas tank, which slowly warms up over a long period and thus requires large amounts to be drawn off continuously.

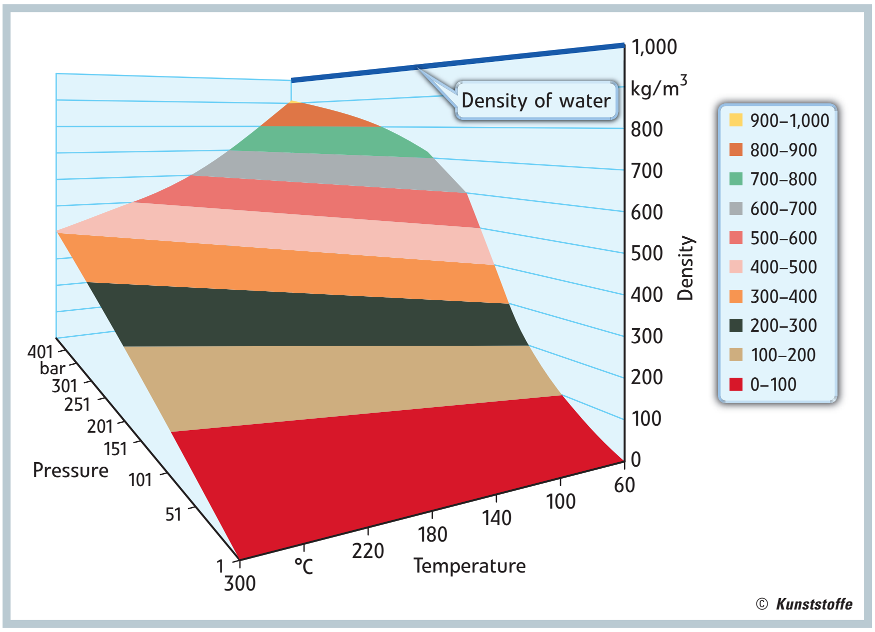

Fig. 1. The density of CO_2 as a function of pressure and temperature. CO_2 can be liquefied at room temperature by raising the pressure to 60 bar; as the pressure rises, its density approaches that of water (source: Maximator)

A Process Flow Which Reduces the Cycle Time

Before the injector forces the gas into the injection mold and thus into the part, it is pressurized in the liquid state effectively from prevailing pressure (60 bar) in the cylinder bundle compresses the gas in the liquid state effectively and with a favorable energy input from 300 to 400 bar. As it is being injected, the CO_2 expands into the melt, displaces the liquid polymer and so forms the cavity in the part. During the subsequent holding pressure time, the remaining melt heats the CO_2 so that, as a result of this intense heat absorption, the gas passes into the supercritical state **(Fig 2)**.

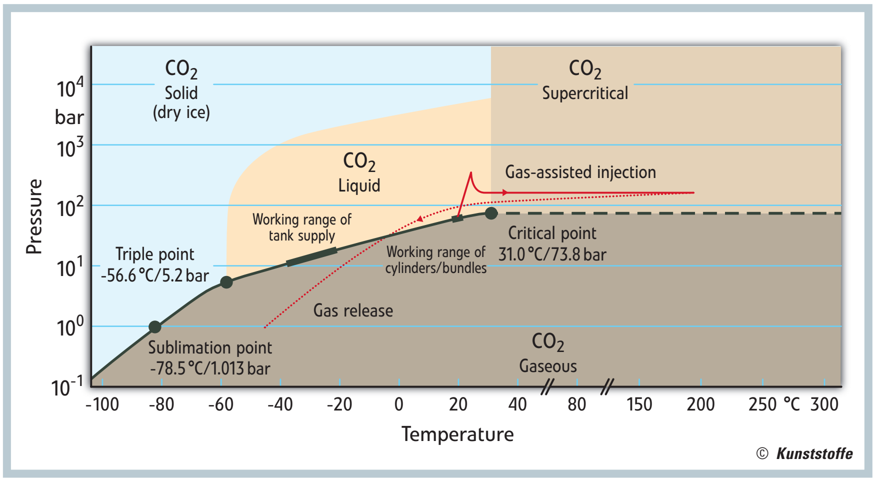

Fig. 2. The phase diagram for carbon dioxide shows the thermodynamics of the CO_2 gas-assisted injection technique where the gas is supplied from cylinders or cylinder bundles

(source: Linde/Maximator/TiK)

At the end of the pressure-holding time, the gas is discharged from the part. The drop in pressure causes a sharp drop in the temperature of the CO_2, and a great deal of heat is extracted from the part. This enormous cooling effect can additionally be utilized to specifically cool hotspots in the injection mold. To successfully employ CO_2- GAIM, processors must observe a few important process details. These concern

- choosing the right injector, and
- avoiding changes in the cross-section of the supply line from the GAIM installation to the injector.

The choice of injector is important for ensuring that gas-assisted injection proceeds smoothly and that discharge is guaranteed [5]. True, this is also the case for nitrogen but, because CO_2 has a much higher density at a given pressure, it takes longer to release it than to release N_2 if the annular gap injectors are too small. The line from the GAIM installation to the injector must not have any changes of cross-section because these would lead to expansion of the CO_2 and the formation of dry ice, which would clog the line.

If users heed these tips, they can implement CO_2-GAIM on most existing GAIM-injection molds that have been previously operated with N_2. Thus, as the following case reports illustrate, the cycle time of many existing GAIM processes can be shortened by an average of more than 25 % merely by replacing the gas and plant engineering **(Fig. 3)** – a joint development by Maximator GmbH, Nordhausen, and Linde AG, Munich, both in Germany.

Putting it Into Practice with Advantage

With the aid of the approach described above, i.e. simply by replacing the plant engineering and the injection gas, Engel Formenbau und Spritzguss GmbH, Sinsheim, Germany, shortened its cycle time for manufacturing a refrigerator handle in the current series by 36 %. A thermal imaging camera is useful here because it enables the temperature distribution in the part to be analyzed immediately after the handle has been automatically removed from the mold **(Fig. 4)**. Direct comparison shows that the handle produced with carbon dioxide can be demolded at a much colder temperature than its counterpart produced with nitrogen. This not only helps to shorten the cycle time, but also improves the warpage behavior.

Similar success was achieved for a dipstick guide tube produced by Gebr. Wielpütz GmbH & Co. KG, Hilden, Germany. The cycle time for this part was shortened by 22 %. Made from a PA6.6 GF30, the part has a very homogeneous (low) temperature of 75 to 80 °C upon removal, which is well below the normal demolding temperature of 120 to 150 °C **(Fig 5)**. With this part, it is not the gas channel which is crucial to shortening cycle times, but rather the machining stage, which the part needs following the injection process.

Excessive shortening of the cycle time would create hotspots at the thicker-walled areas of the holder and ribs. These hotspots are caused by small-sized sliders that cannot be cooled with water. CO_2 serving as a fluid for gas-assisted injection could be used to effect spot cooling, without the need for further process equipment and requiring only a slight modification to the mold; this would shorten cycle times even more, thereby increasing the molded part quality even further.

Fig. 3. The newly developed CO_2-GAIM module installation with integrated liquid booster is suitable for CO_2 and N_2 applications (photo: Maximator)

Fig. 4. The cycle time for producing this refrigerator handle was shortened by more than a third. This thermal image, captured immediately after the process, shows the higher temperature of a handle produced by N_2 (left) compared with that for CO_2-GAIM (right) (photos: Linde)

Synergy Effects for Production Costs and Quality Optimization

Once a strategic decision has been taken in favor of CO_2 as gas injection fluid, further technical ways of lowering production costs and improving part quality emerge:

- spot cooling of injection molds,
- dynamic mold temperature control, and
- the cleaning of injection molds and plastic surfaces (as pretreatment for painting).

In spot cooling **(Fig. 6)**, liquid CO_2 is passed through a flexible capillary tube, 1.6 mm wide at most, to that spot on the molding which needs cooling. There, the CO_2 expands into a chamber, which needs to be provided in the cavity, and effectively cools the region around the expansion chamber [6, 7]. A combination of CO_2-GAIM and spot cooling can be used to supply the CO_2 gas to the hotspot and cool it in the same mold while the gas is being discharged in the GAIM process.

A further application for CO_2 lies in the extremely fast dynamic cavity temperature control of injection molds and mold inserts **(Fig. 7)**. This process, developed jointly by Linde AG, gwk Wärme

Process	Easy to handle	Fluid costs	Investment in plant	Investment in mold	Material costs	Process energy for fluid-assisted injection	Injector size	Cycle time
CO_2-GAIM	++	○	75	100	100	1	+	50
CO_2-GAIM with flushing	+	–	75	105	100	3	○	40
GAIM	++	○	100	100	100	100	+	100
GAIM with flushing	+	–	100	105	100	300	○	80
TiK-WIT	○	+	150	120	130	1	–	50
FAIM cool	○	○	120	100	100	200	+	95

Table 1. Comparison of some fluid-assisted injection processes with different fluids. The percentages are expressed in relation to the nitrogen-GAIM process (= 100 %) (source: TiK)

Fig. 5. At the end of the cycle, the temperature of a dipstick guide tube made from PA6.6 GF30 by CO_2-GAIM is much lower than the normal demolding temperature for such materials, as shown here by the thermal image captured immediately in the 2-cavity mold after the process (photos: Linde)

Kältetechnik mbH, Kierspe, Germany, and Iserlohn Kunststoff-Technologie GmbH, was presented at Fakuma 2012. In it, CO_2 is used to effect both heating and cooling in the same mold insert. To heat the cavity, gaseous CO_2 is heated by means of a compressor and a turbo-heater and passed through the conformal heating-cooling channels of the mold insert. The gas is transported in a closed loop. The mold insert is cooled again by feeding liquid CO_2 into the same heating-cooling channels and relaxing it. The cooling effect is similar to the aforementioned spot cooling. With this technology, temperature gradients of up to 20 K s^{-1} can be achieved for heating and cooling.

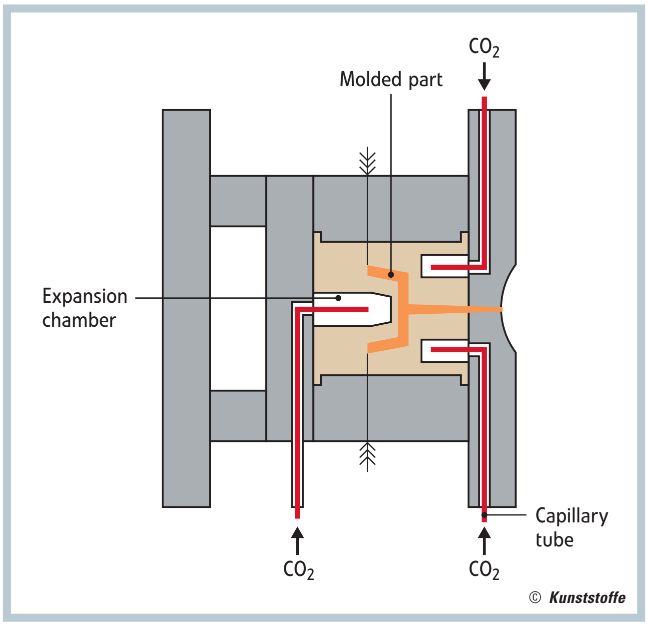

Fig. 6. Schematic structure of an injection mold with spot cooling [6, 7]. The CO_2 cools the region around the expansion chamber effectively (figure: Linde)

Fig. 7. The installation for dynamic mold temperature control combines rapid heating and cooling changes at temperature gradients of up to 20 K s^{-1} (photo: gwk)

Conclusion

Using carbon dioxide as a fluid for the gas-assisted injection technique and slightly modifying the plant engineering is a simple way for injection molding shops to shorten cycle times and lower part costs. Since the process can be handled just as simply as the conversion from nitrogen to CO_2, CO_2-GAIM can improve both current and future GAIM applications. The cleaning effect of the CO_2 on the injectors stabilizes the production processes in the long term. In addition, CO_2 offers an effective and inexpensive way to solve temperature control tasks in injection molding. ■

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